The following is the first of two articles by CPT Robert C. Raiford on the electromagnetic pulse (EMP). The article appearing in this issue deals with the characteristics of EMP and the effects it has on electronics and communications systems. The second article, which will appear in the next issue of TAC, addresses the EMP threat, both tactically and strategically, and design techniques and countermeasures.

by CPT Robert C. Raiford

When you think of a nuclear explosion, you usually think only of the classical effects of the detonation: the shock wave, the heat, the ground shock, the nuclear radiation.

Few people are aware that other phenomena associated with a nuclear blast can severely affect power and communications systems. Temporary blackouts of communications and radar systems, alteration of the basic atomic structure of certain electronic components, and operational upsets or catastrophic failure of electrical and electronic devices are possible. This last effect is directly attributable to the electromagnetic pulse (EMP). of particular interest to defense communications, which is generated by the nuclear explosion.

THE ELECTROMAGNETIC PULSE

The EMP effects of nuclear bursts were first predicted in 1945 by Enrico Fermi and were confirmed by nuclear testing in the 1950s. However, prior to the atmospheric test ban treaty in 1962, no significant interest was shown in learning more about this electromagnetic radiation; its importance was generally ignored.

In 1960, the possible vulnerability of electrical and electronics systems to EMP was recognized. Unfortunately (at least for the field of EMP research), the nuclear test ban treaty followed shortly afterwards and severely limited the amount of empirical data upon which to predict EMP effects. Little unclassified information was available on EMP.

Since the early 1960s, though, EMP has gained importance and is now recognized as an important nuclear weapon threat. Because of the increased susceptibility of electronic systems due to the widespread use of semiconductor devices, EMP is increasingly important. Each of these trends will be discussed in this article; however, to appreciate their significance, a thorough understanding of the characteristics and generation of the EMP is required.

Characteristics of the EMP

> The nuclear EMP is a time-varying electromagnetic radiation which increases very rapidly to a peak and then decays somewhat more slowly. The radiation has a very broad spectrum of frequencies . . . (and)the wave amplitude (or strength) of the radiation varies widely over this frequency range. ("Handbook on Radio Frequency Interference," 1962, Frederick Research Corp.)

Specific quantitative values of EMP are extremely difficult to predict because of the complexity of EMP generation. Accordingly, only qualitative descriptions of EMP characteristics and representative magnitudes are provided in this discussion.

Figure 1 illustrates the spectral analysis of the EMP. Examination reveals an extremely broadband signal ranging from power line to radar frequencies (typically, less than 60Hz to 1-4GHz). It will be noted that the spectral components of the EMP occupy the same frequencies as commercial and military communications systems.

The field strength of an EMP can typically approach 100,000 volts/meter. To place this figure in perspective, consider that a radar beam of sufficient power to cause biological damage has a strength less than 100v/m. Additionally, a transmitted radio signal from a 40,000 watt commercial broadcasting station has a field strength in close proximity to the transmitting antenna of only 1-10v/m.

Figure 2 presents a comparison of EMP and lightning waveforms. Examination of available data indicates that a typical voltage waveform for EMP has a rise time of 10 nanoseconds (10 times faster than that of lightning) and a duration on the order of one microsecond.

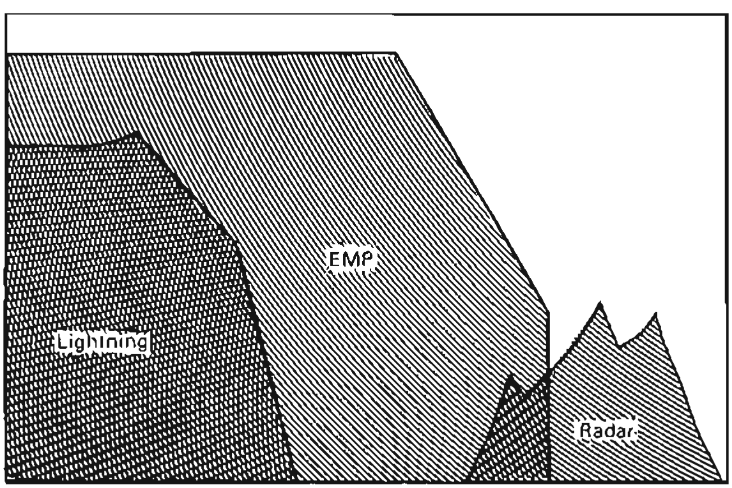

Figure 1. Spectral analysis of the EMP.

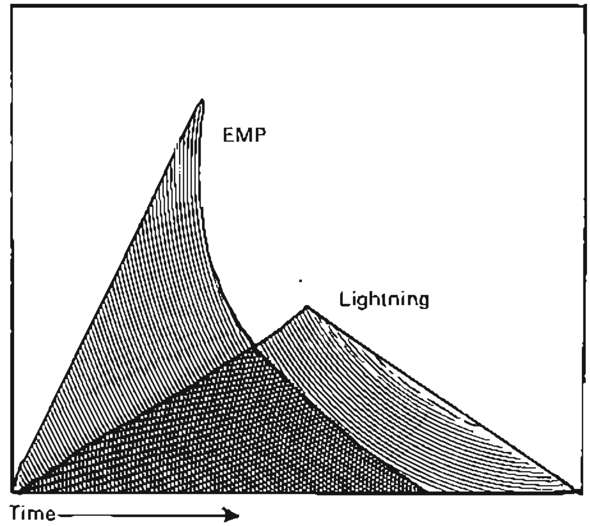

Figure 2. Comparison of EMP and lightning waveforms.

Two other characteristics of EMP which are of particular interest to military and commercial systems are: (1) EMP's extremely great "killing" range (up to 4,800 kilometers); and (2) EMP's presence when all other prompt nuclear weapon effects are absent.

Generation of the EMP

EMP is a prompt nuclear detonation effect which arrives at target locations along with thermal radiation and initial nuclear radiation well in advance of the shock wave. While the actual composition of each EMP is unique, the generation follows the same energy transformation process.

The first step in the conversion is the release of gamma rays during a nuclear explosion. As these high energy gamma photons speed away from the burst point, they collide with air molecules. Upon impact, the photon is either partially or completely absorbed by an electron. The photon's energy is imparted to the electron in the form of kinetic energy. Like a billiard ball struck by the cue ball, this electron speeds off in the same general direction of the incident photon leaving behind a positively charged ion. This electron is referred to as a Compton recoil electron, and the process is called the Compton effect.

In a homogeneous atmosphere, the burst point is surrounded by a source region defined by a rapidly expanding outer shell of Compton electrons and a more slowly expanding inner shell of the heavier ions. The positively charged ions are continually seeking to regain their lost electrons. This attraction results in a current flow which can radiate electromagnetic energy. As long as the source region is symmetrical, however, there will be no net current flow and no EMP will be generated.

In actuality, the source region can never be symmetrical, and some net current will flow. Asymmetries produced in the near surface tactical burst and the high altitude or exoatmospheric burst are of particular military interest and are discussed separately below.

Near Surface Burst

At burst altitudes below 2 km, the resulting source region is essentially hemispherical in shape with size dependent upon weapon yield. Typically, the source region will be 3 to 8 km in diameter for tactical surface bursts yielding less than 40 kilotons.

Downward-traveling gamma rays will be absorbed by the ground. Those traveling upward and outward will produce charge separation through the Compton effect. The charge separation in the horizontal plane will be shorted by the greater conductivity of the earth, leaving only a vertical charge separation producing a net vertical electron current. At the same time, the electrons returning through the ground to the positively charged region of the burst point form a loop current producing strong azimuthal magnetic fields as illustrated in Figure 3.

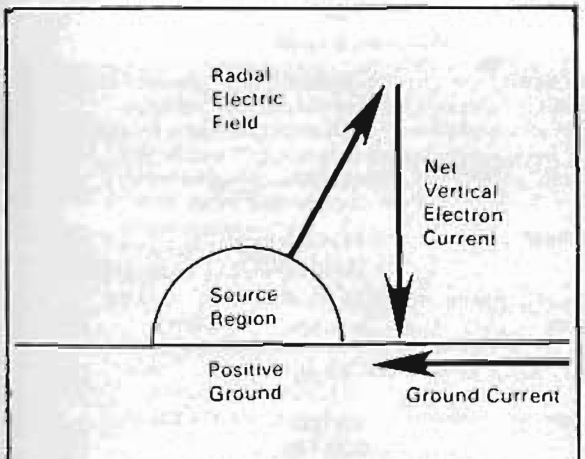

Figure 3 Current flow in source region

The source region thus appears as a vertical dipole antenna radiating electromagnetic energy in the form of a sharp pulse. This field is very strong near the source region; but it falls off rapidly with distance, exhibiting the same characteristics as communications signals in groundwave propagation. The EMP is not considered to be militarily significant beyond 15 km for a surface burst of 3 to 40 kilotons.

High Altitude Burst

At burst altitudes in excess of 40 km, asymmetry of the source region is caused by the atmospheric density gradient and the earth's geomagnetic field. Gamma rays traveling upward encounter very few air molecules at these altitudes and move long distances before being absorbed. Gamma rays traveling downward, however, will encounter a region of increasing density of air molecules. Between altitudes of 20 to 40 km, the atmospheric density is great enough to allow formation of a source region.

This source region is pancake-shaped with a size limited only by the curvature of the earth (see Figure 4). Within the source region, the Compton electrons are deflected by the earth's magnetic field and are forced to spiral about the field lines. This spiralling action produces a transverse Compton current and is the primary mechanism for EMP generation in exoatmospheric bursts.

The EMP produced by a high altitude burst is essentially a downward-traveling plane wave with a substantially uniform intensity reaching 10^4 volts/meter over an area extending thousands of kilometers from ground zero.

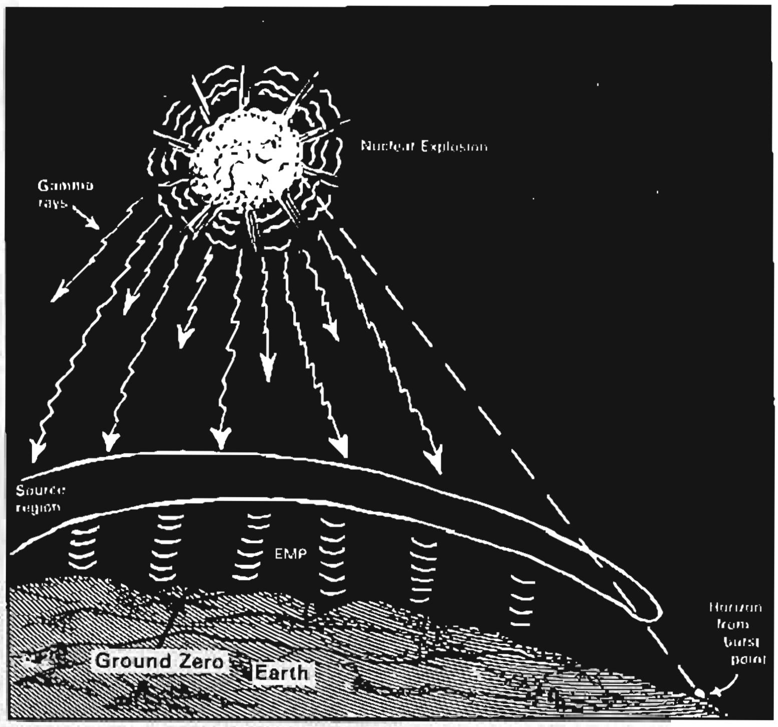

Figure 4. Source region of high altitude burst.

The polarization of the high altitude EMP is a function of the location of the burst, the location of the observer and the direction of the earth's magnetic field. As a rule of thumb, the polarization of the electric field is normal to both the direction of propagation (radially outward from the burst point) and the earth's magnetic field at the location of the observer.

The polarization can vary from horizontal to vertical. For most of the United States and western Europe, the expected polarization would range from horizontal to 30° to 40° off horizontal. Those desiring expected polarizations for other regions should consult Stacey's "Physics of the Earth."

Effects of the Electromagnetic Pulse

The EMP in itself is not harmful. Theory and experiment show that EMP is generally harmless to living tissue. Only when the EMP has been collected by metallic conductors does it unleash its tremendous power in the form of voltage and current surges. This effect is comparable to sunlight on paper. Unaided sunlight merely warms the paper; but if it is focused by a magnifying lens, its power is concentrated and the paper will ignite. Likewise, electrical wires, antennas and other forms of collectors focus EMP energy to cause devastating results in sensitive equipment to which they are connected. As a general rule, the amount of energy collected increases with the dimensions of the conductor (or antenna). It must be emphasized here that EMP affects equipment and has no direct effect on wave propagation.

The EMP effects to be considered in this article fall into two categories: (1) functional damage and (2) operational upset. Functional damage is catastrophic, permanent failure, such as the burn-out of a transistor. Operational upset is a temporary impairment or malfunction of a system, such as the change of state in flip-flop circuits.

Before examining specific effects on components and systems, it will be helpful to understand the three modes of coupling EMP energy to electrical circuits, i.e., electric induction, magnetic induction and resistive coupling.

In electric induction, a current is induced in a conductor proportional to the cosine of the angle between itself and the impinging electric field. Conductors oriented parallel to the polarization of the EMP will therefore have a maximum current induced.

Magnetic induction occurs in conductors that form closed loops. The current induced in these loops is proportional to the sine of the angle between the plane of the loop and the orientation of the magnetic field. The form of the loop is immaterial. The fuselage of an airplane or the reinforcing bars in concrete can constitute a loop in this respect.

Resistive coupling occurs when a conductor is immersed in a conducting medium, such as ionized air, salt water or the ground. For example, current induced in the ground by one of the other coupling modes will "see" the conductor (buried cable or ground stake) as an alternate conducting path and flow in it.

Electrical and Electronic Components

The effect of EMP on electronic equipment was first demonstrated during atmospheric testing in the early 1950s. It has since been determined that the main threat to components is the induced transient voltage and current surges generated by EMP-system interaction. Table 1 gives some typical values for EMP-induced surges on conductors.

Semiconductor devices are the most sensitive to EMP effects. The primary cause of failure in semiconductor devices is junction breakdown caused by excessive heat created across the junction. As the junction area becomes smaller, the susceptibility of the device to EMP-induced failure increases. Microminiature circuitry produced by large scale integration processes is extremely sensitive to total functional damage unless specifically protected—an extremely difficult task in itself. See Table 2 for estimated EMP energy tolerances of several typical components.

TABLE 1

EMP-INDUCED SURGES ON CONDUCTORS

Type of Conductor	Rise Time (Seconds)	Peak Voltage (Volts)	Peak Current (Amperes)
Long, unshielded wires (power lines)	10^{-8}-10^{-7}	10^{5}-5×10^{6}	10^{3}-10^{4}
Unshielded telephone line	10^{-8}-10^{-6}	10^{2}-10^{4}	1-100
AC power line at wall plug	10^{-7}-10^{-5}	10^{3}-5×10^{4}	10-100
HF antennas	10^{-8}-10[illegible]	10^{4}-10^{6}	500-10^{4}
VHF antennas	10^{-9}-10^{-8}	10^{3}-10^{5}	100-10^{3}
UHF antennas	10[illegible]-10^{-8}	100-10^{4}	10-100
Shielded cable	10^{-6}-10^{-4}	1-100	0.1-50

SOURCE: Dr. C.R. Fisher, Dr. D.B. Nelson, and P.R. Barnes, "EMP and the Radio Amateur," SQT, September 1975.

TABLE 2

TABLE OF ESTIMATED ENERGY REQUIRED TO DEGRADE CHARACTERISTICS OF SELECTED DEVICES

Microwave diodes	10^{-7} joules
Integrated circuits	10^{-5} joules
Semiconductor diodes	0.1-1.2×10^{-5} joules
Transistors	2-100×10^{-5} joules
Relays	2-100×10^{-3} joules
Vacuum tubes	1 joule

SOURCE: L.W. Ricketts, J.E. Bridges, and J. Miletta, EMP Radiation and Protective Techniques, (New York: John Wiley and Sons, 1976), p. 76.

Peak EMP-induced voltages in long overhead power lines can range up to 900 kilovolts with current surges ranging to 3,000 amperes. These transients are sufficient to cause component damage ranging from burned out transistors and resistors to vaporized coils and exploding transformers.

EMP effects on cables and wires are also significant. Sheath currents can be generated on signal cables with sufficient strength to rupture the cable insulation. Cables which are already stressed (such as antenna transmission lines) can undergo dielectric melting or breakdown. Even if the cable can withstand the EMP-induced transient, the voltage can propagate along the conductors and appear as a damaging potential at the nearest repeater or terminal. The worst case tests have shown that such voltages can exceed 100 kilovolts with sheath currents of 80 kiloamperes in aerial telephone cable.

Power and Communications Systems

The EMP effect on individual components can be devastating as shown above. When these components are interconnected to form systems, the complexity and effect of EMP is multiplied. In a process termed the "avalanche effect," a small amount of EMP-induced energy can dump huge amounts of stored electrical energy (by disrupting timing or protective circuits, for example), causing a "landslide" which could destroy components or jam communications systems.

The fact that unprotected telephone systems could easily collect enough EMP energy to either temporarily or permanently knock out switching centers and long lines multiplexing equipment was recognized by the Bell Telephone System prior to 1969.

System EMP effects vary from system to system, based primarily on component technology and signal levels can easily exceed these low signal thresholds even when the EMP is so weak as to pose no physical threat to even the most sensitive integrated circuit. The effects from these false signals are generally temporary, but may range from a minor upset, such as a parity error, to serious calculation or control errors depending upon the processor's particular function and design. For example, a processor mistake in a fire control calculation could seriously endanger friendly forces.

TABLE 3

DEGREES OF SUSCEPTIBILITY TO THE EMP

Most Susceptible

Low-power, high-speed digital computer, either transistorized or vacuum tube (operational upset)

Systems employing transistors or semiconductor rectifiers:

- *Computers and power supplies*
- *Semiconductor components terminating long cable runs, especially between sites*
- *Alarm systems*
- *Intercom systems*

Life-support system controls

- *Some telephone equipment which is partially transisitorized*
- *Transistorized receivers and transmitters*
- *Transistorized 60 to 400 Hz converters*
- *Transistorized process control systems*
- *Power system controls and communication links*

Less Susceptible

Vacuum tube equipment that does not include semiconductor rectifiers:

Transmitter	*Intercom systems*
Receivers	*Teletype-telephone*
Alarm systems	*Power supplies*

Equipment employing low-current switches, relays, meters:

Alarms	*Panel indicators and status boards*
Life-support systems	*Process controls*
Power systems control panels	

Other:

- *Long power cable runs employing dielectric isulation*
- *Equipment associated with high-energy storage capacitors*
- *Inductors*

Least Susceptible

High-voltage 60 Hz equipment:

Transformers, motors	*Rotary converters*
Lamps (filament)	*Heavy-duty relays, circuit breakers*
Heaters	*Air-insulated power cable runs*

SOURCE: Samuel Glasstone and Philip J. Dolan, ed., The effects of Nuclear Weapons, 3rd ed. (Washington, D.C.: Government Printing Office, 1977), p. 525.

employed. Table 3 provides a listing of typical devices and their relative susceptibility to EMP damage.

Digital Systems

Computer systems' applications have rapidly entered almost every facet of modern life. Each new generation of digital processors is faster and smaller than the one before. Unfortunately, these characteristics make computers more susceptible to EMP damage or upset. The smaller the components, the less capable they are of dissipating heat caused by EMP-induced transients and the greater the probability of failure.

The computer's reliance on peripheral magnetic memory devices provides another weak spot for EMP effects to exploit. Magnetic induction via head drives and transistorized core drivers may be sufficient to erase or alter information stored on tapes, disks and in ferrite cores.

Failure to execute prescribed shutdown procedures often results in computer operational program loss. The probability that EMP-induced power interruption will be preceded by fuse-blowing transients negates any benefit from alternate battery power.

The low threshold voltages used in logic circuitry provide a fourth significant vulnerability to EMP effects. EMP-induced transients in data buses and signaling lines

Satellites

In addition to the serious consequences of direct bombardment by gamma rays and high neutron fluences resulting from an exoatmospheric burst, satellites may experience operation upset or even functional damage caused by an EMP wave which has been reflected by the earth.

Power Systems

By their very nature, power systems provide excellent coupling with EMP. High altitude EMP, which is predominantly horizontally polarized, couples very efficiently with overhead power lines causing voltage and current surges capable of damaging anything hooked into the system. Lightning arrestors and circuit breakers are much too slow to eliminate the first pulse, but they may provide some protection from subsequent pulses.

The effects of EMP on power systems do not rely exclusively on theoretical predictions and simulated tests as do some of the other effects discussed here. The best authenticated case of EMP-induced failure of a power system occurred following STARFISH, a high-altitude (450 km) 1.4 megaton burst in the Johnston Island area of the Pacific Ocean in 1962. On the Hawaiian island of Oahu, 1,280 kilometers from ground zero, 30 strings (series-connected loops) of street lights failed simultaneously, hundreds of burglar alarms in Honolulu began ringing, and numerous power line circuit breakers opened. The street lights failed because the fuses protecting the various strings had blown. These failures were attributed to the same EMP transients that opened the circuit breakers and triggered the burglar alarms.

EMP susceptibility is not limited to commercial power systems. Emergency power generators used by hospitals, commercial microwave transmission facilities, and Civil Defense and military operations centers are also vulnerable. Remote control leads, generator exciter controls, battery charging circuits, and the power feed lines themselves can couple EMP energy into the system, damaging both the generator and the emergency circuits.

Communications Systems

The broad frequency range of the EMP makes almost all currently used unhardened and unprotected communications equipment subject to EMP interference or damage. The major exception is equipment operating in the microwave region above 4 GHz where the EMP intensity diminishes quite rapidly. Microwave dish antennas will not pick up enough energy to damage most related circuits. Tests of an antenna used with a microwave radio repeater showed essentially no pick-up by the horn feed. (It must be noted, however, that damaging transients can still enter through power and signal circuits.)

Unhardened and unprotected equipment in the high and very high frequency ranges, on the other hand, is quite susceptible to EMP problems. Experiments have demonstrated that VHF whip antennas on walkie talkies can collect enough energy to destroy the front-end transistor unless special protection is provided.

Tests on 7.5-meter vertical monopole antennas have shown that fields of EMP strength can induce peak open circuit voltages of 260 kilovolts and peak short circuit currents of 1,200 amperes 25 nanoseconds after arrival of the pulse. Peak voltage into a 50Ω load reached 50 kilovolts—sufficient to break down any known, unprotected semiconductor junction! Any unhardened and unprotected military single-channel radios currently in use are particularly susceptible to damage caused by such high potentials appearing across their sensitive radio frequency amplifiers. EMP energy can futher enter the radio set via power, microphone, and remoting cables and apertures in the case.

The division tactical multichannel radio operates in the UHF spectrum. It is used in line of sight systems which consequently may require numerous terminal and relay antennas. These antennas are of corner reflector, high gain design and can amplify an EMP entering from the proper angle. They are also capable of collecting energy over a 200 to 500 MHz band depending on the particular dipole used. This combination of high gain and wide bandwidth makes any unhardened and unprotected radio receiver connected to these antennas extremely vulnerable to EMP. The high intensity pulse would immediately overload the frequency converter, which is power sensitive. It is very doubtful that the detector circuitry could survive this pulse.

The multichannel radio found in corps and area systems also operates in the UHF spectrum. Its vacuum tube design makes it a "harder" radio as far as EMP susceptibility is concerned. However, it is still subject to damaging transients induced in power cables, equipment cables and excessively long (over 30 meters) coaxial antenna feeds.

Unhardened and unprotected switchboards, patch panels and communications centers are extremely vulnerable. EMP-induced currents in signal cables can cause considerable arcing and burning. The extremely fast rise time of these transients negates any benefit from lightning arrestors. The 26-pair cable commonly used to interconnect these communications shelters is not shielded. Currents induced in it would be of such magnitude that arcing and dielectric failure would occur.

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